Semiochemicals of rose aphid, black citrus aphid (Hemiptera: Aphididae) and greenhouse thrips (Thysanoptera: Thripidae)

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ABSTRACT

Macrosiphum rosae L. or rose aphid, *Toxoptera citricida* Kirkaldy or black citrus aphid (Hemiptera: Aphididae) and *Heliothrips haemorrhoidalis* Bouché or greenhouse thrips (Thysanoptera: Thripidae) are serious cosmopolitan phytophagous pests that can cause severe damage to many cultivated crops.

The aim of this study was to investigate the chemical signals utilized by these pests in order to carry out their everyday functions. This was achieved by determining the nature of volatile compounds in the secretions of the rose aphid, the black citrus aphid and the greenhouse thrips.

The results obtained showed similarities not only between the two aphid species but also between aphids and thrips with acids and their methyl esters, aldehydes and alkanes being common components of the secretions.

E-β-farnesene, a known alarm substance in many aphid species, was confirmed to be a constituent of the secretions of the rose aphid and was isolated for the first time from the black citrus aphid. Results indicated that the sesquiterpene is metabolically produced by the insects and used when required.

Key words: Rose aphid, Black citrus aphid, Greenhouse thrips, Aphididae, Thripidae, Volatiles, *E*-β-farnesene, Secretions, Semiochemicals.

INTRODUCTION

Rose and black citrus aphids

Aphids are considered serious agricultural and horticultural pests (Hill 1997). They cause major damage to crops by their feeding, and, more importantly, by transmitting various plant viruses that are pathogenic to their hosts (Schepers 1987). In addition, "honeydew" excreted by the aphids attracts saprophytic fungi which cover the leaves leading to reduction of photosynthetic capacity of the host plant (Schepers 1987).

Toxoptera citricida Kirkaldy or black citrus aphid (Hemiptera: Aphididae), is oriental in origin and is widespread world-wide (Carver 1978). *T. citricidus* exhibits a distinct preference for citrus and a few other members of the Rutaceae (Carver 1978). In Australia *T. citricida* has been reported to restrict growth of its hosts and affect fruit setting (Hely 1968) due to its feeding.

Macrosiphum rosae L. or rose aphid (Hemiptera: Aphididae), is also a cosmopolitan pest that can cause severe damage to various members of the Rosaceae (Hill 1997). This pest may have various hosts during the year, however, it is most commonly found feeding on roses (Mound and Teulon 1995).

All aphids are characterized by two specialized, tube-like structures which protrude from the dorso-lateral surface of the posterior part of the abdomen called siphunculi or cornicles (Dixon and Stewart 1975). Many aphid species escape from their predators by producing "an oily liquid from their siphunculi" which they smear on the mouthparts of the attacking predator (Büsgen 1891). Escape is facilitated by the rapid solidification of the cornicle droplet and the resulting immobilization of the attacking predator or parasitoid (Miyazaki 1987). Furthermore, it was reported that green peach aphids (*Myzus persicae* Sulzer) are repelled by the "odour" of droplets released from the cornicles of crushed aphids of the same species (Kislow and Edwards 1972). Subsequently it was found that the sesquiterpene hydrocarbon *E*-β-farnesene is utilized as an alarm pheromone in several economically important aphids including *M. rosae* L. (Bowers *et al.* 1972; Edwards *et al.* 1973).

Greenhouse thrips

Heliothrips haemorrhoidalis Bouché or greenhouse thrips[1] (Thysanoptera: Thripidae), is a minute, slender-bodied insect (1–2 mm in length) that occurs outdoors in warmer climates and in greenhouses in the colder regions of the globe (Borror *et al.* 1992). It is a cosmopolitan, polyphagous pest and can cause severe damage to both agricultural and greenhouse crops (Beattie and Jiang 1990; Hill 1997; Lewis 1973) feeding on young and mature leaves and fruits (Mound and Teulon 1995). Greenhouse thrips cause damage to their host not only by feeding, but also by depositing anal excrement on the surface of the leaves or fruits. Although the flesh is not damaged, the grade of the fruit is reduced (Beattie and Jiang 1990).

The number of biological observations dealing with thrips secretions is limited perhaps due to the small size of these insects. Nevertheless, adults of many thrips species are known to raise and lower their abdomens when disturbed whilst some thrips adults and larvae produce a drop of anal exudate in order to deter predators (Froggatt 1906; Buffa 1911; Lewis 1973; Suzuki *et al.* 1990).

Secretions emitted by many species within the sub-order Tubulifera have been the subject of chemical investigations. Compounds identified so far include: γ-decalactone (Howard *et al.* 1983), perillene (Suzuki *et al.* 1986), cetyl and myristyl acetates (Suzuki *et al.* 1988), 3- and 5-dodecenoic acids (Haga *et al.* 1989), β-acaridial (Suzuki *et al.* 1989), β-myrcene (Haga *et al.* 1990), mellein (Blum *et al.* 1992) and plumbagin (Suzuki *et al.* 1995).

Secretions from species within the sub-order Terebrentia have not been investigated to the same extent as those from tubuliferous species. The western flower thrips, *Frankliniella occidentalis* Pergande was, until this study the only terebrantious species to have had its secretion chemically analysed. Decyl and dodecyl acetates were reported as constituents of the anal exudate (Teerling *et al.* 1993a), a mixture of which was found to have pheromonal (Teerling *et al.* 1993a) and kairomonal properties (Teerling *et al.* 1993b).

The objectives of this study were to determine the nature of volatile organic chemicals in the secretions of *T. citricidus* and *H. haemorrhoidalis* and to expand on the earlier chemical analysis of the secretions of *M. rosae*. The possible biological function of the compounds identified is discussed.

MATERIALS AND METHODS

Insects

The aphids used in this study were collected daily during winter from host plants located in Richmond (New South Wales, Australia). *T. citricida* was collected from a round kumquat *Fortunella japonica* tree, whilst *M. rosae* was collected from hybrid tea roses *Rosa hybrida*.

Greenhouse thrips from a four year old laboratory culture were used. The culture was established from field collected specimens (Richmond, New South Wales, Australia). The thrips were reared on lime fruits *Citrus aurantifolia* at 28°C with a photoperiod of 16 hours.

T. citricida and *H. haemorrhoidalis* specimens were identified by Assoc. Prof. G. A. C. Beattie (Former Senior Research Scientist, New South Wales Department of Agriculture). *M. rosae* specimens were identified by Assoc. Prof. R. N. Spooner-Hart (Horticulture Precinct, University of Western Sydney, Hawkesbury).

Collection of insect volatile secretions

i) *Solvent extraction* — Fifty mixed adults and nymphs of each insect species (only adults for the thrips) were crushed in liquid nitrogen to a fine powder, which was then extracted with hexane (3 mL). The extract was then concentrated to 100 μL.

ii) *Headspace above crushed insects* — One hundred mixed adults and nymphs of each insect species (only adults for the thrips) were placed in a 2 mL vial and were crushed with a metallic pin through the cap. The headspace above the crushed insects was sampled (at room temperature) for 1 hour using polar and non-polar solid phase micro-extraction (SPME).

iii) *Direct collection of the cornicle/anal exudate* — To collect aphid secretions, aphids of all stages were placed under a stereo microscope and were prodded gently on their head and thorax with a metallic pin. The cornicle exudate released by the aphids was collected on polar and non-polar SPME fibres (Sigma-Aldrich Pty. Ltd., New South Wales, Australia) by touching 10 cornicle droplets with the end of the fibres.

Anal exudate from greenhouse thrips nymphs was collected in a similar way to that described above. However, in this case the nymphs were not prodded. The anal exudate is carried by the nymphs on the tip of their abdomen as they "walk around".

[1]Thrips will be used for both, singular and plural forms.

Analysis of the insect volatile secretions

The volatiles obtained from above were analysed by gas chromatography (GC) and gas chromatography coupled mass spectrometry (GC-MS).

GC analysis was performed using a HP 6890 gas chromatograph equipped with a flame ionization detector and a HP 7673 GC/SFE auto-injector. The column used was 50QC2/ BPX-5 (SGE Scientific, Melbourne, Australia).

GC-MS analysis was carried out on a HP5890 Series II gas chromatograph connected to a HP 5971A mass selective detector. The column used was BP-1 (SGE Scientific, Melbourne, Australia).

Compounds were identified based on mass spectral evidence and by comparison of their retention time to those of authentic samples.

RESULTS

Rose and black citrus aphids

Qualitatively the results obtained from the black citrus and the rose aphids were almost identical (Fig. 1). *E*-β-farnesene was present in solvent and headspace extracts of whole crushed individuals from both species; the same compound was also found to be a component of the cornicle droplets produced by aphids when attacked. Long chain alkanes, acids and their methyl esters, and aldehydes were also isolated from both aphid species. An unknown sesquiterpene (which is believed to be an α-farnesene isomer based on mass spectral evidence) was present in the secretions of the rose aphid but was not detected in those from the black citrus aphid. A complete list of the compounds identified and their source is given in Table 1.

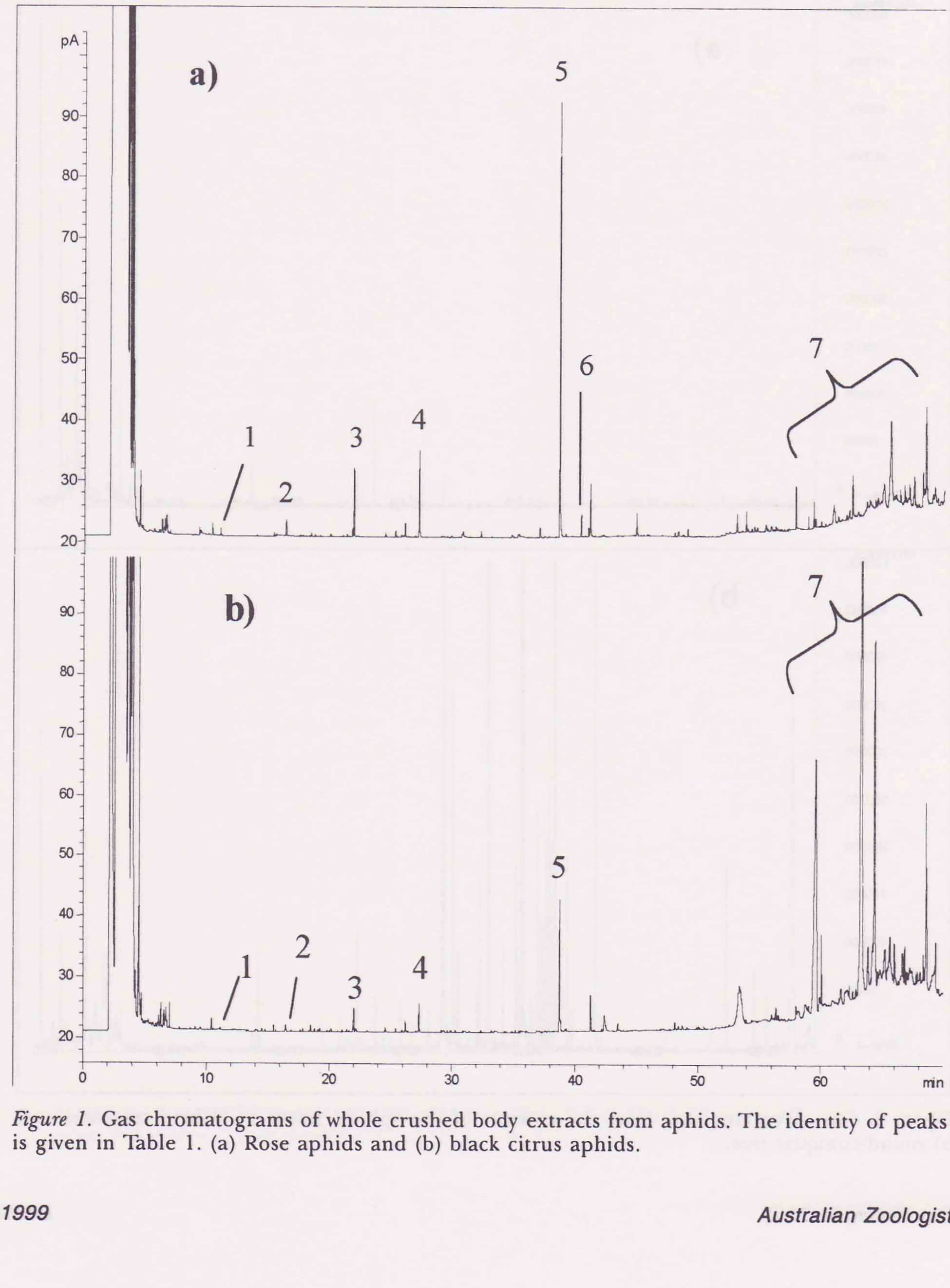

Figure 1. Gas chromatograms of whole crushed body extracts from aphids. The identity of peaks is given in Table 1. (a) Rose aphids and (b) black citrus aphids.

Table 1. Volatile components in the secretions of the rose and black citrus aphids and their source. Bold numbers in brackets refer to Figure 1.

Source	Rose aphid volatiles	Black citrus aphid volatiles
Whole crushed body solvent extraction	alkanes (C_{19}–C_{27}) (**7**), decanal (**4**), *E*-β-farnesene (**5**), hexanoic acid (**1**), methyl hexanoate (**2**), nonanal (**3**), α-farnesene isomer (**6**)	alkanes (C_{19}–C_{27}) decanal, *E*-β-farnesene, hexanoic acid, nonanal
Headspace above crushed aphids	α-farnesene isomer, decanal, *E*-β-farnesene, nonanal	γ-terpinene, decanal, *E*-β-farnesene, limonene, nonanal
Cornicle droplet	alkanes (C_{14}–C_{18}), α-farnesene isomer, decanal, *E*-β-farnesene, nonanal	alkanes (C_{14}–C_{18}), decanal, *E*-β-farnesene, nonanal

None of the volatiles present in secretions from black citrus and rose aphids (Table 1) were found in extracts from the aphids' hosts. As expected the volatile profiles of the two hosts, round-kumquat tree and hybrid tea roses, were totally different (Fig. 2).

Greenhouse thrips

Long chain alkanes, acids (and their methyl esters) and aldehydes were isolated from the solvent extracts of whole crushed adult greenhouse thrips. Previously reported (Njoroge *et al.* 1996) citrus volatiles such as

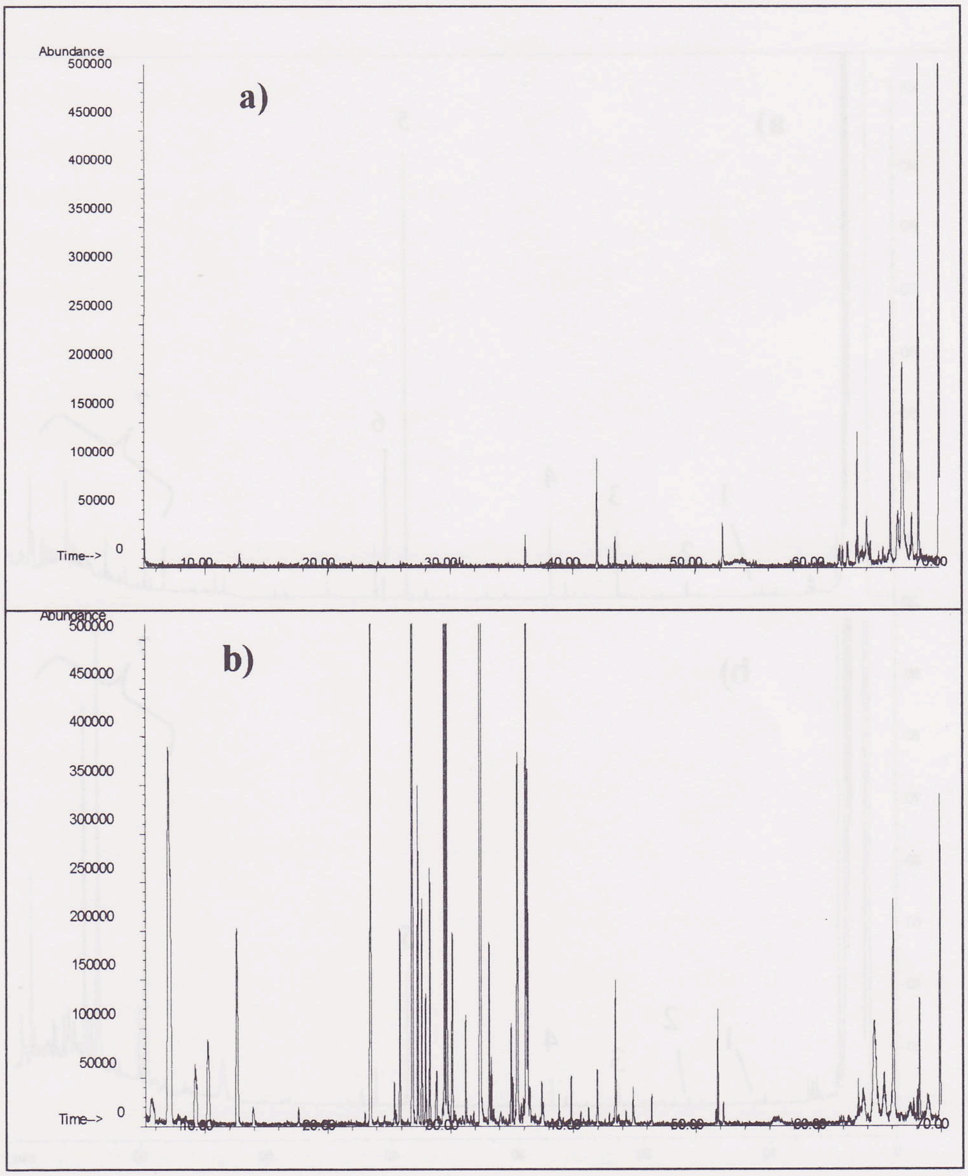

Figure 2. Gas chromatograms from the extracts of the aphids' hosts. a) Hybrid tea-roses and b) round-cumquat tree.

monoterpenes and sesquiterpenes were identified as constituents of the headspace above crushed adult greenhouse thrips. The saturation of the insects' body with lime volatiles during rearing is the most probable cause of the above result. Long chain alkanes, coumaran (Fig. 3a) and 3-methoxy-acetophenone (Fig. 3b) were identified as constituents of the anal fluid produced by greenhouse thrips' nymphs. A complete list of the compounds isolated from the thrips' secretions and their source is given in Table 2.

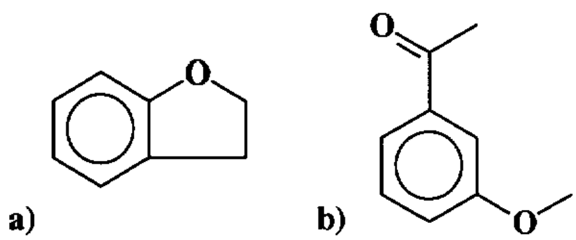

Figure 3. Structures of some compounds found in secretions of greenhouse thrips: a) Coumaran and b) 3-methoxyacetophenone.

Table 2. Volatile components in the secretions of the greenhouse thrips and their source.

Source	Greenhouse thrips volatiles
Whole crushed body solvent extraction	alkanes (C_{20}, C_{22}–C_{23}), decanal, hexanoic acid, methyl tetradecanoate, methyl hexadecanoate nonanal
Headspace above crushed aphids	β-bisabolene, γ-terpinene, *E*-ocimene, geranyl acetate, limonene, neryl acetate
Cornicle droplet	alkanes (C_{14}–C_{17}), coumaran, 3-methoxyacetophenone

DISCUSSION

Rose and black citrus aphids

E-β-farnesene has been identified as an alarm substance in several economically important aphids, including the rose aphid (Bowers *et al.* 1972). This study confirmed the presence of *E*-β-farnesene in the secretions of the rose aphid and in addition showed that this sesquiterpene is also a component of the secretions of the black citrus aphid.

The minor qualitative differences observed between the secretions from the two aphid species may be very important biologically. Synergistic effects to the activity of *E*-β-farnesene have been so far attributed to α-pinene (vetch aphid) and a mixture of *(E,E)*-α- and *(Z,E)*-α-farnesene (green peach aphid) (Pickett and Griffiths 1980). Therefore it is possible that compounds such as limonene, *E*-ocimene and γ-terpinene for the black citrus aphid and the α-farnesene isomer for the rose aphid, may be important in producing the alarm response synergistically with *E*-β-farnesene in the present aphid species.

Two aldehydes, nonanal (C_9) and decanal (C_{10}), were identified in secretions from both aphid species. Aldehydes are odorous and irritant in nature and many are known to be employed as constituents of the defensive secretions of many other hemipteran species, especially pentatomid bugs (Waterhouse *et al.* 1961; Aldrich 1988). Their presence in the cornicle droplet of both rose and black citrus aphids suggests that they are utilized as defensive allomones against aphid predators.

The other identified components of the secretions (carboxylic acids and their methyl esters, long alkanes) are known to be associated with all insects' exoskeleton and cuticle (Borror *et al.* 1976) and it is unlikely they are involved in insect chemical communication.

Greenhouse thrips

A mixture of decyl- and dodecyl- acetates was found to be utilized as an alarm" pheromone by the western flower thrips (Teerling *et al.* 1993a). The headspace above crushed adult greenhouse thrips (Table 2) contained the stereoisomers neryl- and geranyl-acetate; it is possible that a mixture of the two may elicit alarm response in the greenhouse thrips. However, the two isomers were found to be constituents (in small amounts) of the oil obtained from limes (Njoroge *et al.* 1996) and therefore it is possible the two acetates were found in the headspace extracts due to the saturation of the greenhouse thrips' body during rearing. There is no evidence to support or refute possible biological activity.

The two aldehydes (nonanal and decanal) found in aphid secretions were also encountered in secretions of greenhouse thrips. However, it appears that these are not the only defensive allomones employed by greenhouse thrips. The function of coumaran (2,3-dihydro-benzofuran) and 3-methoxy-acetophenone (Fig. 3), determined to be components of the anal fluid produced by greenhouse thrips' nymphs, is believed to be similar to that of the two aldehydes. Acetophenone-based products are known insect repellents and are widely employed for that purpose during field studies (Torr *et al.* 1996). 3-Methoxyacetophenone is also known for its bird-repellent properties (Clark *et al.* 1991). Benzofuran-based products appear to be toxic to several insect species and recently, two naturally occuring hydroxy-benzofuran derivatives were found to be toxic against spruce budworms (Findlay *et al.* 1997).

It appears that thips nymphs employ a greater variety of natural products for their protection than the adults. This may be related to the fact that the adults posses other means to avoid predation such as flying, while the nymphs do not have this option (Lewis 1973).

Comparison between aphids and thrips

The results obtained from the chemical analysis of secretions from aphids (Order: Hemiptera) and thrips (Order: Thysanoptera) support the phylogenetic theory proposed by Kristensen (1991) according to which, the two insect orders have evolved from a common ancestor (Sub-division: Paraneoptera). The qualitative analysis of the secretions emitted by aphids and thrips showed that there are many compounds or groups of compounds common to the two orders and this suggests a relationship between the Hemiptera and the Thysanoptera. Aphids and thrips exhibit a similar secreting behaviour and the common components of their secretions may be associated with that behaviour.

Effect of diet on insect secretions

Most compounds identified in aphid secretions were absent from extracts of the aphid hosts. This suggests that *E*-β-farnesene and most of the other components of the secretions are metabolically synthesized by the rose and black citrus aphids. Similarly, it is likely that the volatile components identified within the anal fluid produced by greenhouse thrips nymphs are metabolically produced. The volatile constituents of lime oil have been reported to be monoterpenes, sequiterpenes and hydrocarbons; components identified within the anal fluid were not found as constituents of the lime oil (Njoroge *et al.* 1996).

Some compounds, such as *E*-β-farnesene and aldehydes, were found to be components of the aphid cornicle fluid and, were also present in the solvent extracts derived from crushed aphids. The presence of these compounds in the solvent extracts indicates that they were found within the aphids' body at the time of sampling. This suggests that the above volatiles are produced and subsequently stored within the aphids' body until required.

An "opportunistic observation" was made during this project: the removal of rose aphids from their host for a period of 12 hours was found to decrease their ability to produce cornicle fluid. Therefore, it is likely that nutrients derived from the host are utilized as precursors for the metabolic production of the natural products contained within the cornicle fluid.

There are many differences between the chromatograms obtained from the two aphid hosts (Fig. 2). However, the chromatograms produced from the whole, crushed body extracts of the two different aphid species are almost identical (Fig. 1). This suggests that various metabolites are utilized as precursors by different metabolic pathways for the production of the chemicals emitted by the aphids. *E*-β-farnesene is known to be secreted by several economically important aphid species that feed on different hosts (Bowers *et al.* 1972; Edwards *et al.* 1973). It is likely that different metabolites are found in different host plants. Therefore, the metabolic pathways utilized by each aphid species are possibly modified according to their diet in order to synthesize common semiochemicals such as *E*-β-farnesene.

Future work

If behavioural studies were to be carried out to determine the activity (if any) and the biological function of the compounds identified during this study, the active chemicals could then be incorporated into modern IPM strategies for pest control. Examples of other insect-derived natural products already used in IPM strategies for pest control include the alarm substances citral and isopiperitenone which are used to synergize the effects of acaricides against mites (Kuwahara *et al.* 1987; Howse *et al.* 1998).

Secretions from the insect species in this study could be analysed for the presence of non-volatile semiochemicals possibly by high performance liquid chromatography (HPLC). Aphid and thrip parasitoids are known to locate their host using contact pheromones (non-volatile compounds) (Budenberg 1990) therefore, future investigations in this area could be rewarding.

CONCLUSION

Many volatile organic compounds were identified as constituents of the secretions emitted by the rose aphids, the black citrus aphids and the greenhouse thrips. The inter-specific aphid alarm pheromone *E*-β-farnesene was identified in secretions from the black citrus aphid for the first time. Many of the identified components appear to be utilized for defensive purposes by the above pests and results obtained indicated that they are metabolically produced and stored until required. However, the qualitative composition of the secretions emitted by the above pests does not depend to a great extent on their diet. Behavioural studies are required to determine which of the compounds identified from the secretions could be incorporated in modern IPM strategies for improved control of the above pests.

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